

# AMBR\* Engine for Science Missions

*NASA In Space Propulsion Technology (ISPT) Program*

*\*Advanced Material Bipropellant Rocket (AMBR)*



July, 2008



- ☐ **Overview**
- ☐ **Objectives**
- ☐ **Benefits**
- ☐ **Heritage**
- ☐ **Results To-Date**
- ☐ **Remaining Tasks**

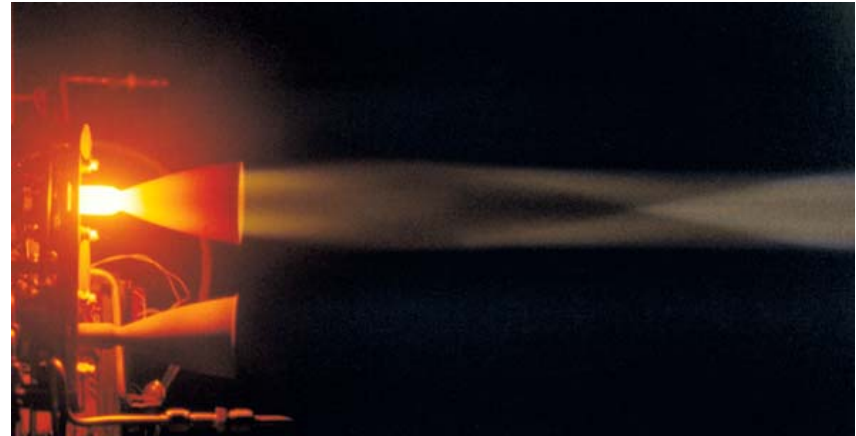


# NRA High Temperature Bipropellant Thruster (AMBR)



## Objective

- Improve the bipropellant engine Isp performance by fully exploiting the benefits of advanced thrust chamber materials
- Goals
  - \* 335 seconds Isp with NTO/N<sub>2</sub>H<sub>4</sub>
  - \* 1 hour operating (firing) time
  - \* 200 lbf thrust
  - \* 3-10 years mission life



## Approach

- Adopt operating conditions to allow the thruster to run at higher temperatures and pressures
- Test a baseline engine for model development
- Evaluate materials and fabrication processes
- Develop advanced injector and chamber design
- Fabricate and test a prototype engine
- Environmental testing: life hotfire, vibe, and shock tests

## Key Milestones/Upcoming Events

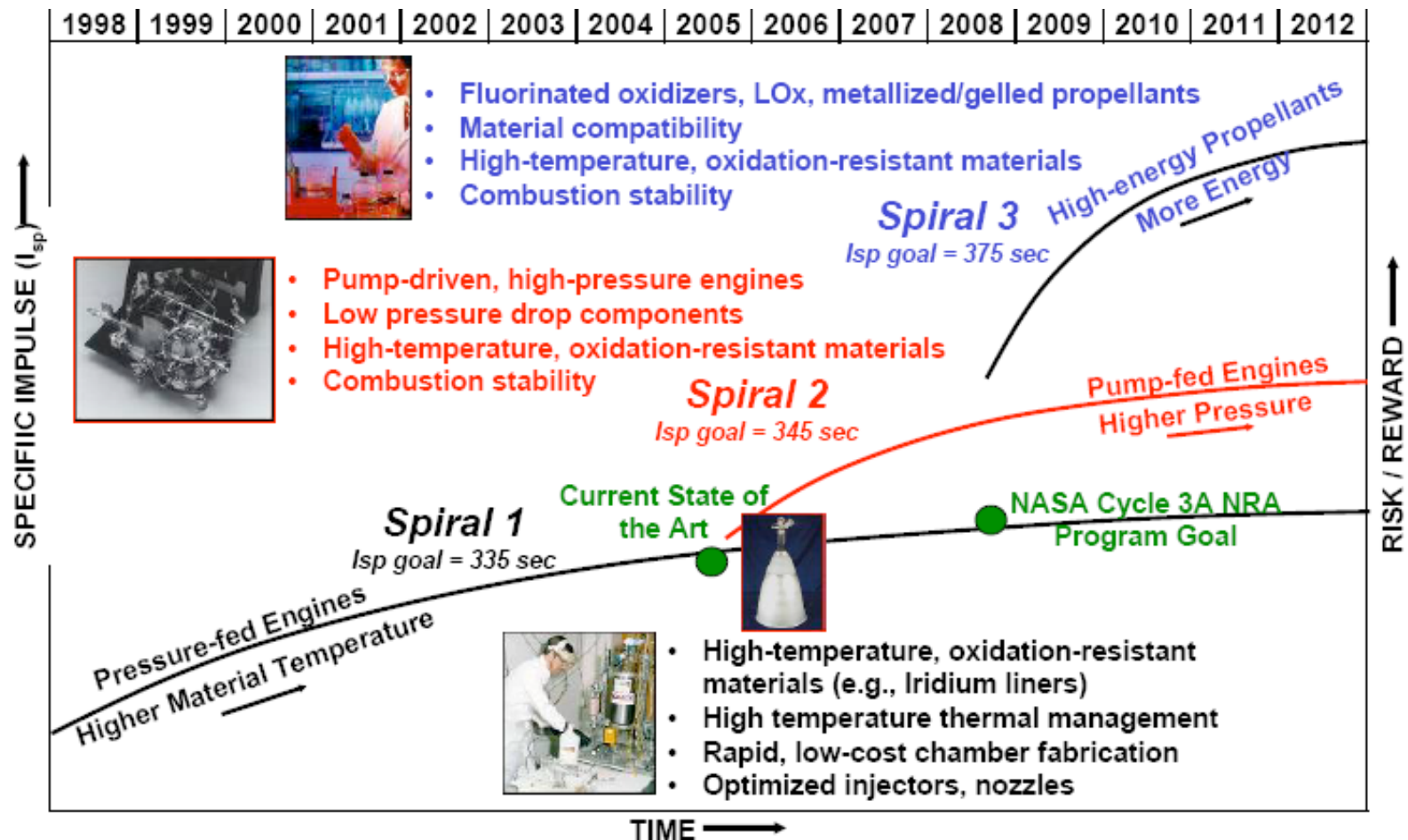
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| • Kickoff                         | Sept 2006  |
| • Mission and System Analysis TIM | Dec.       |
| • Baseline Testing                | Feb. 2007  |
| • Risk Mitigation Chamber Testing | Nov.       |
| • Prototype Engine Testing        | Sept. 2008 |
| • Environmental Testing           | Nov.       |



# AMBR Thruster within a Technology Plan



## Technology Advancement Spirals







# Goals for AMBR Thruster Development



## Primary Goal

- ❑ Design and test an Ir-lined Re storable bipropellant apogee class engine to demonstrate
  - 335 seconds steady-state Isp with NTO/N<sub>2</sub>H<sub>4</sub>
  - 3-10 years mission life (by analysis & similarity)
  - 1 hour operating (firing) time
  - 200 lbf thrust

## Secondary Goal

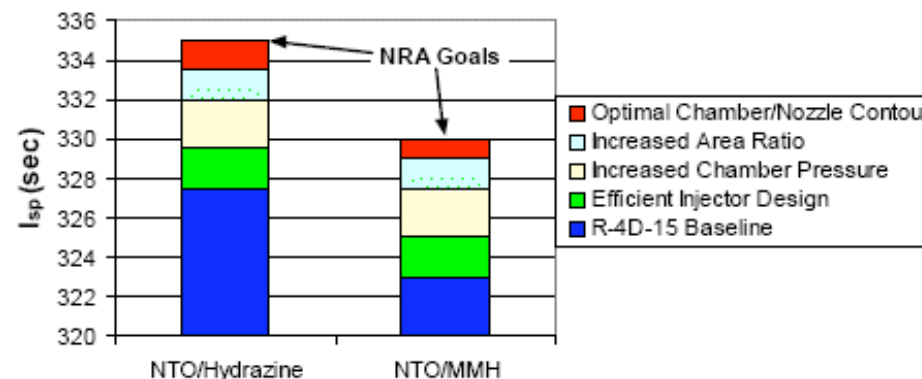
- ❑ Investigate viability of alternate Ir/Re fabrication processes and other related material systems
- ❑ Determine whether alternate processes offer cost, producibility, and/or performance advantages over the baseline chemical vapor deposition (CVD) Ir/Re fabrication process (EI-Form has been found to reduce manufacturing cost by 30% over CVD)



# Design for Higher Performance



- ❑ **Modify Aerojet's state of the art engine design such that the chamber wall materials operate at their temperature limits while maintaining safety margins critical to mission integrity**
  - Optimized injector
  - Optimized chamber/nozzle contour
  - Reduced chamber emissivity
  - Increased thermal resistance between injector and chamber
- ❑ **Change engine operating conditions (within mission constraints), which will produce higher combustion gas temperatures**
  - Higher feed pressure/lower internal pressure drop
  - Higher/optimized mixture ratio

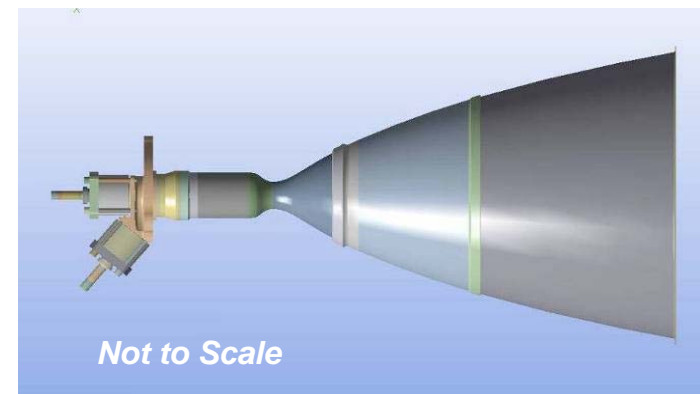
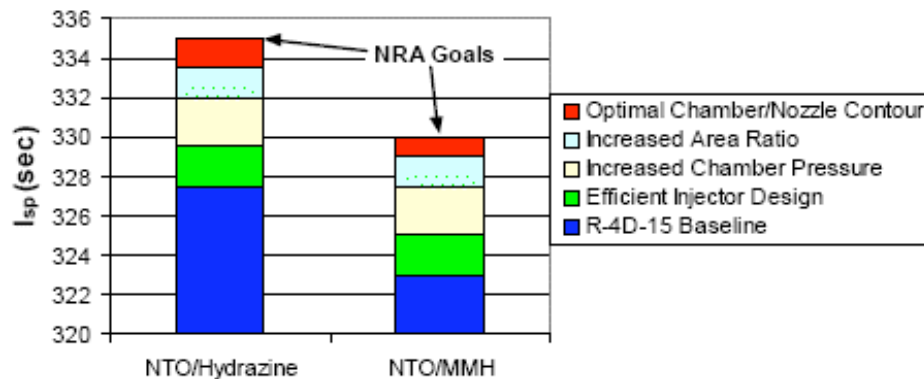




# Design for Higher Performance



<u>Design Characteristics</u>	<u>AMBR</u>	<u>HiPAT DM</u>
• Trust (lbf)	200	100
• Specific Impulse (sec)	335	328
• Inlet Pressure (psia)	400	250
• Chamber Pressure (psia)	275	137
• Oxidizer/Fuel Ratio	1.2	1.0
• Expansion Ratio	400:1	375:1
• Physical Envelope	Within existing HiPAT envelope	
• Propellant Valves	Existing R-4D valves	





# Mission and System Studies Show Benefit



- ❑ Conducted mission and system studies to identify propulsion technology requirements and impacts

AMBR Engine potential mass reduction for the missions

- Results show increased performance can reduce the propellant required to perform spacecraft maneuvers.

- Propellant reduction implies increase of payload

	Total Propulsion System Mass Reduction (Kg)				
Isp (sec)	320	325	330	332.5	335
GTO to GEO	0	16	30	37	45
Europa Orbiter	N/A	0	12	16	24
Mars Orbiter	N/A	0	14	22	29
T - E Orbiter	N/A	0	29	45	60





- ❑ The AMBR technology is an improvement upon the existing HiPAT™ engine
- ❑ The HiPAT™ engine is a member of the Aerojet Corporation's R-4D Family of thrusters
- ❑ The R-4D family of thrusters carries the heritage: >1000 engines delivered, >650 flown, 100% success rate



# AMBR Baseline Thruster Test



Europa DM HiPAT Development Engine



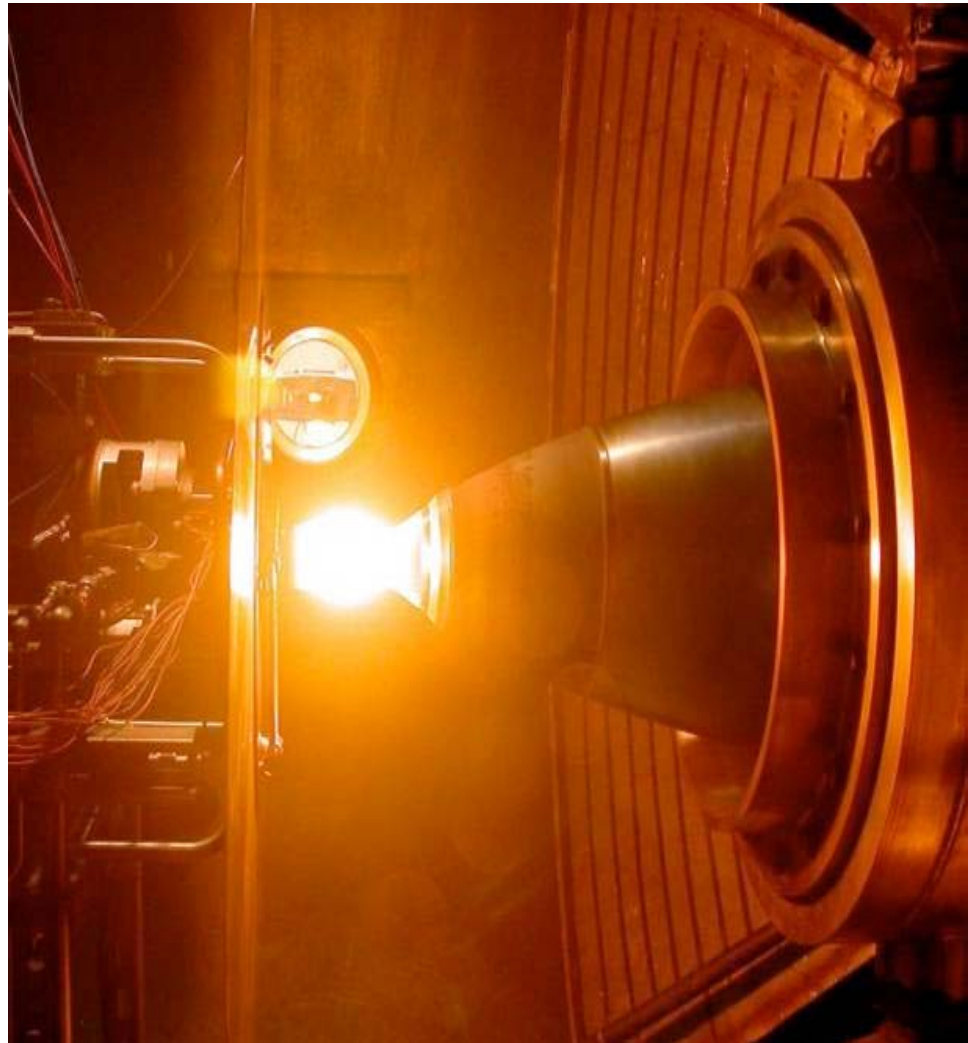
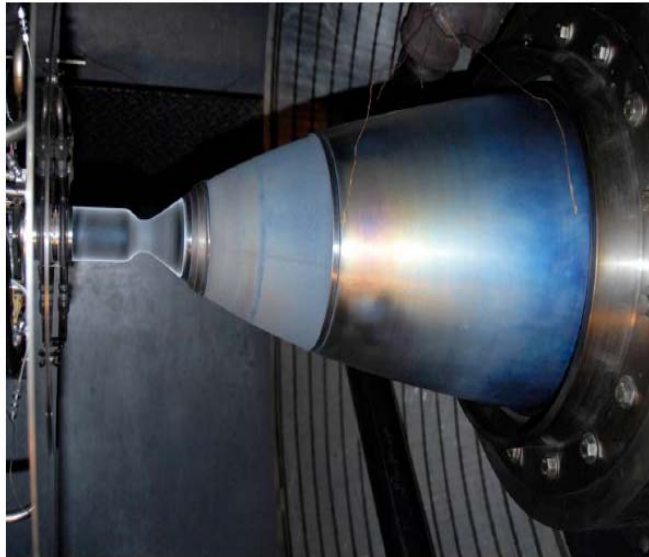
Astrium S/N 008 HiPAT Flight Engine

## **Baseline test article assembled from**

- Workhorse R-4D development valves
- Europa R-4D-15DM HiPAT development engine injector/step assembly
- Astrium S/N 008 R-4D-15 HiPAT flight engine chamber/nozzle

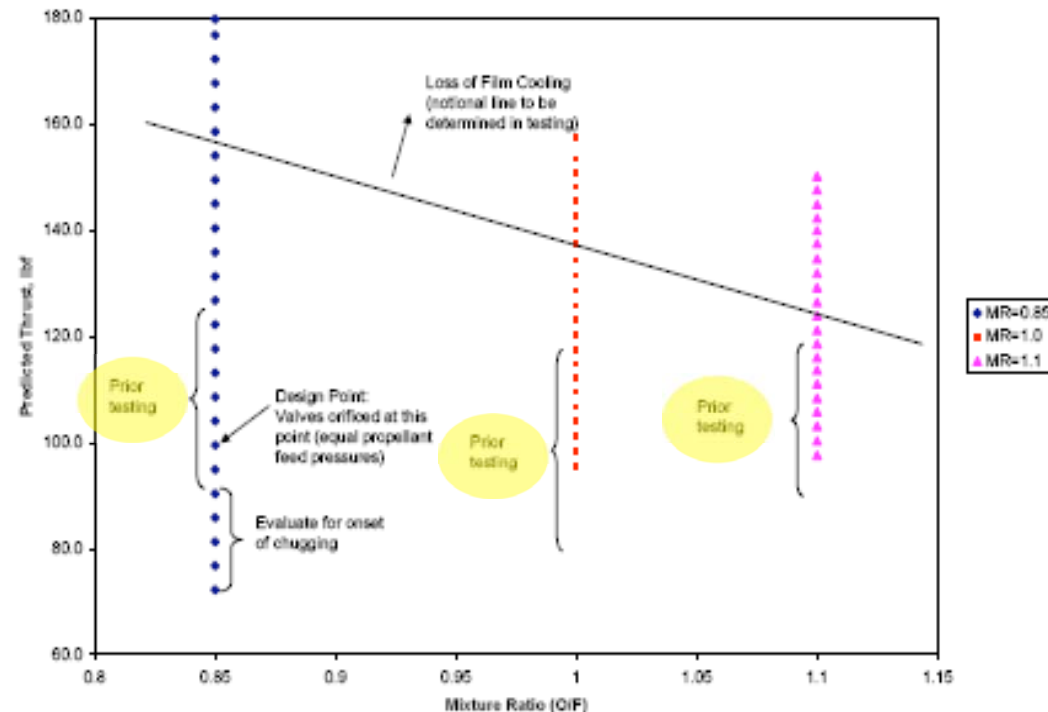


# Thruster Installed and Fired





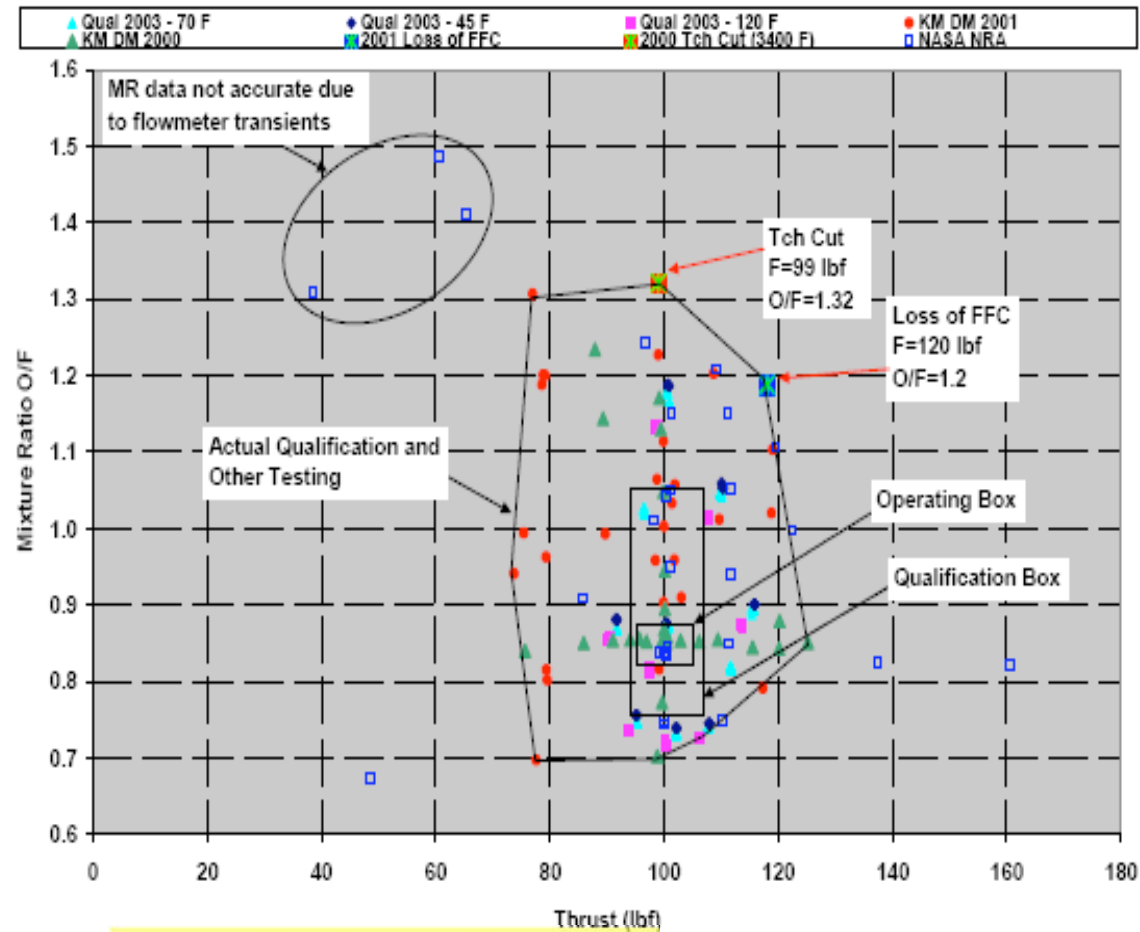
# AMBR Baseline Test Matrix



- **Baseline test matrix**
  - Primary goal to achieve high temperature, high chamber pressure data
  - Matrix if fully realized would utilize all budgeted propellant
- **Test matrix extended during test program as propellant became available**
  - Not all proposed test points could be achieved due to loss of film cooling



# Baseline Test Map



- R-4D-15DM tested to extreme conditions during this test program
- Higher chamber pressures could be attained with this engine with better thermal management



## Baseline Test – Key Results Summary



- 26 hot fire runs over four days
- 2909 seconds of total burn time
- Propellant consumption
  - 472 lbm NTO
  - 569 lbm N<sub>2</sub>H<sub>4</sub>

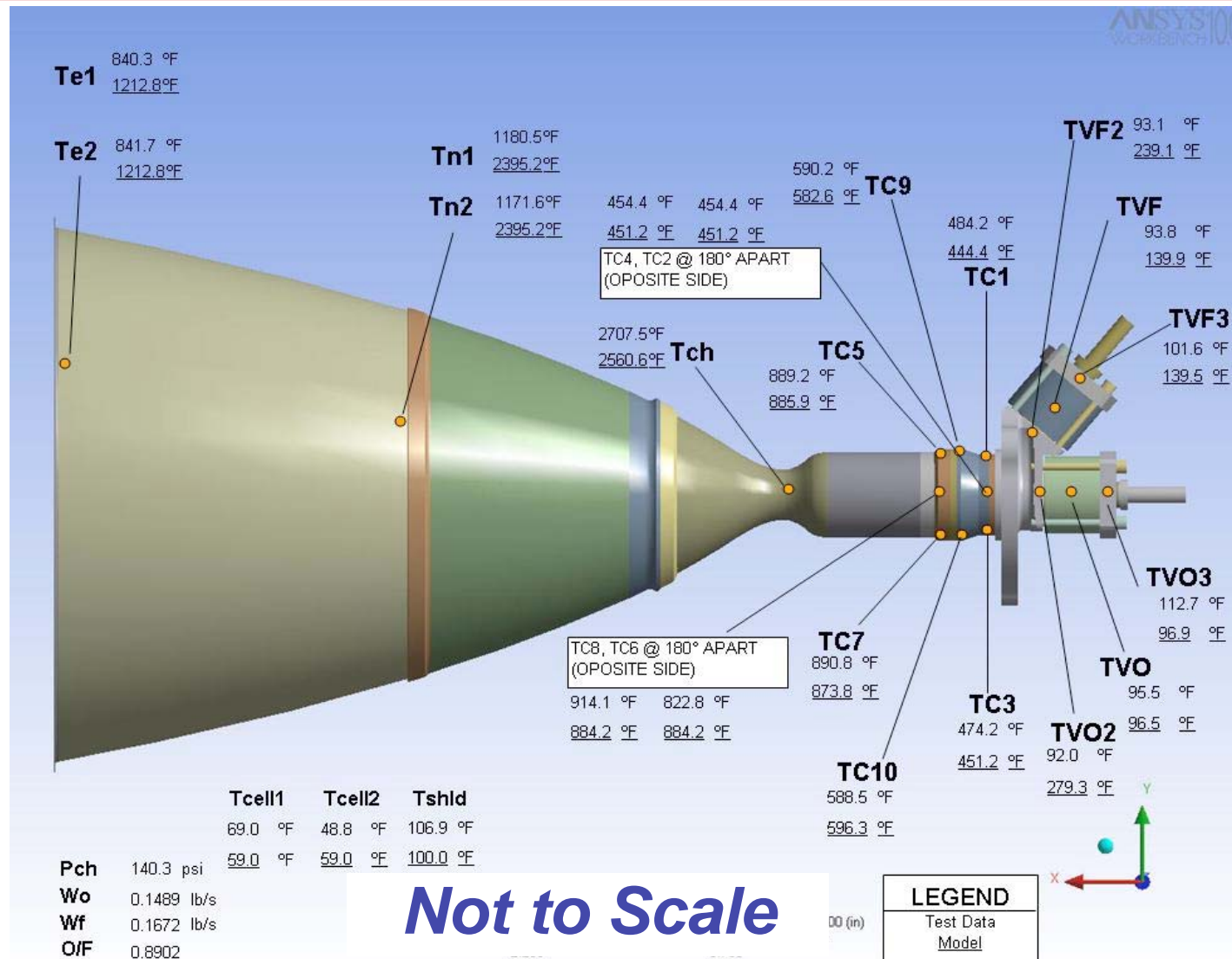
	<i>Test Value</i>	<i>New Design</i>
PC	217 psia	275 psia
Isp	329 sec	335 sec
TC	3673 F	4000 F-- Mat'l Capability

- 3673 F maximum chamber temperature
- 217 psia maximum chamber pressure (prior max of 160 psia)
- 53.4 psia minimum chamber pressure (prior min of 99.4 psia)
- 329 seconds maximum specific impulse (prior max of 328.3 sec)
- Platinum step temperatures successfully collected (data not previously obtained)
- Exterior chamber/nozzle temperatures successfully collected via new IR camera (data not previously obtained)
- Data collected has been very important to the subsequent prototype design



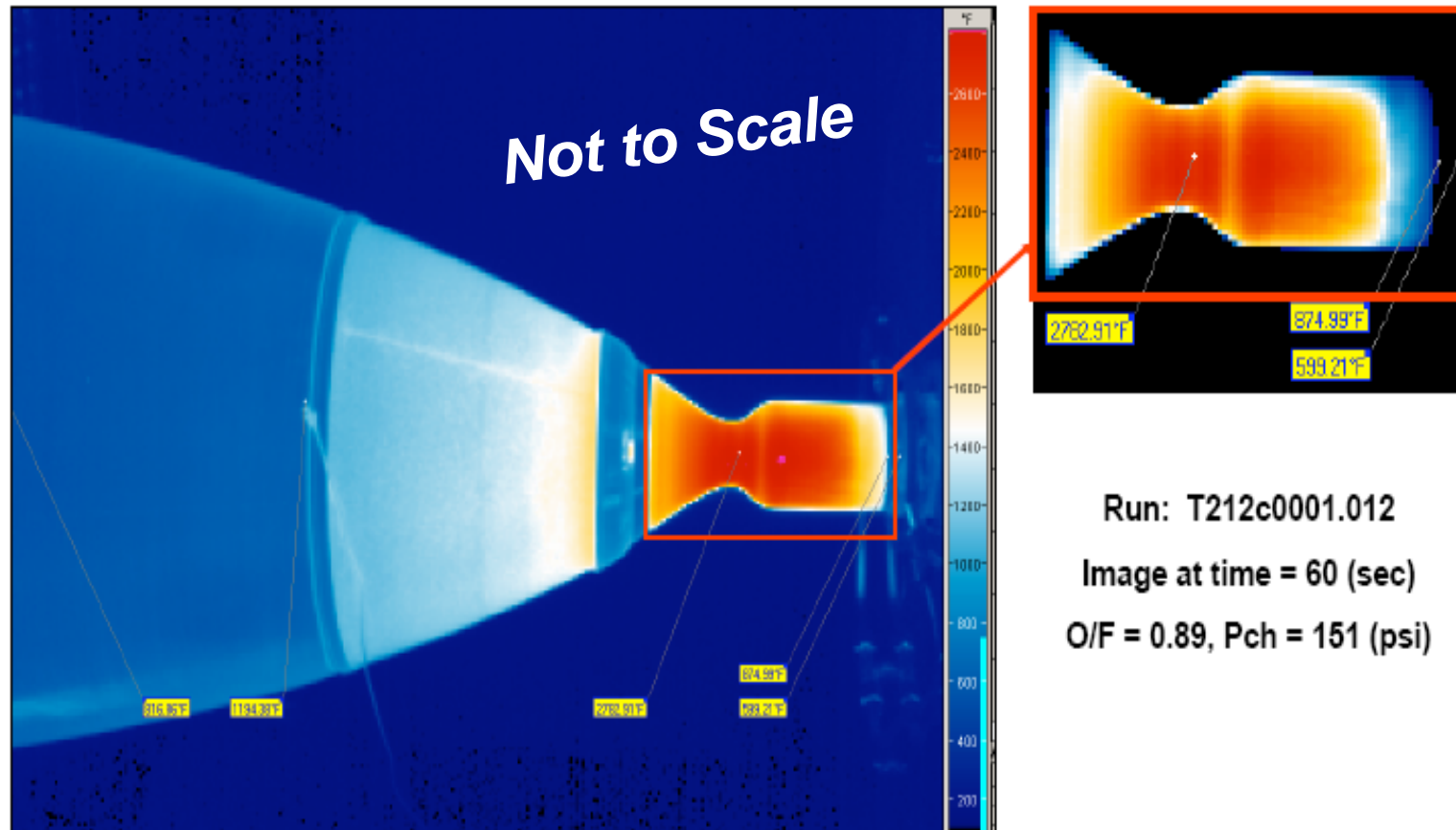


# Anchoring Thermal Model w/ Test Data





## Baseline Test – Thermal Camera Output



- Thermal Camera temperatures at each indicated point shown are correlated to thermocouple and pyrometer data. Overall temperature scale (color bar) is correlated to the chamber emissivity.



# AMBR Thruster Design Detail



- ❑ Defined internal **chamber and nozzle contours**
- ❑ Finalized iridium layer thickness and an envelope that would contain the final rhenium thickness distribution
  - Using R-4D-15DM random vibration spectrum for structural calculations
- ❑ Evaluated design concepts for the injector chamber interface and pre-combustor step assembly to accomplish
  - Optimization of thermal design
    - Basic thermal model completed
    - Anchoring **thermal model** to baseline engine test data
  - Minimization of high cost materials
  - Simplification of fabrication and construction
- ❑ Performed additional injector development test with copper chamber to mitigate risk during the design phase
  - Injector performance and chamber length validated via  $C^*$
  - Resonator design verified
  - Goal of Isp 335 second is achievable



## Selection of High Temperature Chamber Materials & Fabrication



- ☐ Iridium coated Rhenium (Ir/Re) chamber selected
- ☐ Assessed: Chemical Vapor Deposition (CVD), electroforming (El-Form™), Low Pressure Plasma Spray (LPPS) and Vacuum Plasma Spray (VPS)
- ☐ CVD is the incumbent process used to fabricate the R-4D-15 HiPAT™ thrust chambers
- ☐ El-Form has been used to fabricate an Ir/Re chamber for a bipropellant engine
- ☐ LPPS and VPS were dropped due to low technical maturity.
- ☐ **Figures of Merit used** for the decision matrix were:
  - ☐ Producibility
  - ☐ Cost – Recurring & nonrecurring
  - ☐ Schedule – Recurring & nonrecurring
  - ☐ Performance – Mechanical properties, thermal, oxidation resistance, & mass
  - ☐ Heritage/Risk – Design & manufacturing
- ☐ **The El-Form process was down selected** primarily due to the low production cost



# Chamber Materials Candidate Evaluation



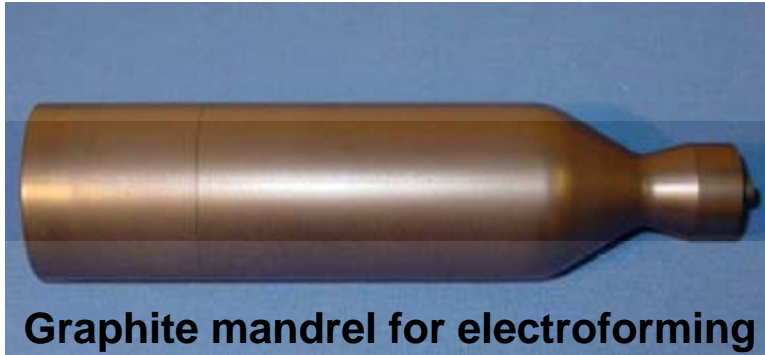
Candidate Material/Process	Cost/Schedule	Pros	Cons
Engineered EL-Form Rhenium (Re)	▪ High (but likely in scope)	▪ Improved YS and UTS	▪ Process repeatability compared to traditional EL-Form Re not known ▪ Elevated temperature strength and life not known
Thick EL-Form Ir layer	▪ Moderate	▪ Improved life	▪ Increased chamber life not demonstrated
Functionally graded ceramic lined Ir/Re ( $\text{HfO}_2$ or $\text{ZrO}_2$ )	▪ Out of Scope	▪ Increased operating temperature and life ▪ Improved oxidation resistance	▪ Low TRL ▪ Significant process development/testing needed
VPS Ir/Re	▪ Out of Scope	▪ Low cost ▪ High tensile strength ▪ Thicker Ir	▪ Significant process development and testing required
HIP bonded Ir /Re	▪ Out of Scope	▪ Thicker Ir ▪ Improved Re process repeatability ▪ Improved properties	▪ Thrust chamber fabrication process not well known ▪ Complex fabrication ▪ High cost
Dispersion strengthened Mo/Re or other advanced alloy	▪ Out of Scope	▪ Reduced weight ▪ Lower cost ▪ Improved elevated temperature strength	▪ Significant development and testing required ▪ Joining characteristics not well known

Life Test Scheduled...





# El-Form™ Chamber Fabrication Process



**Graphite mandrel for electroforming**

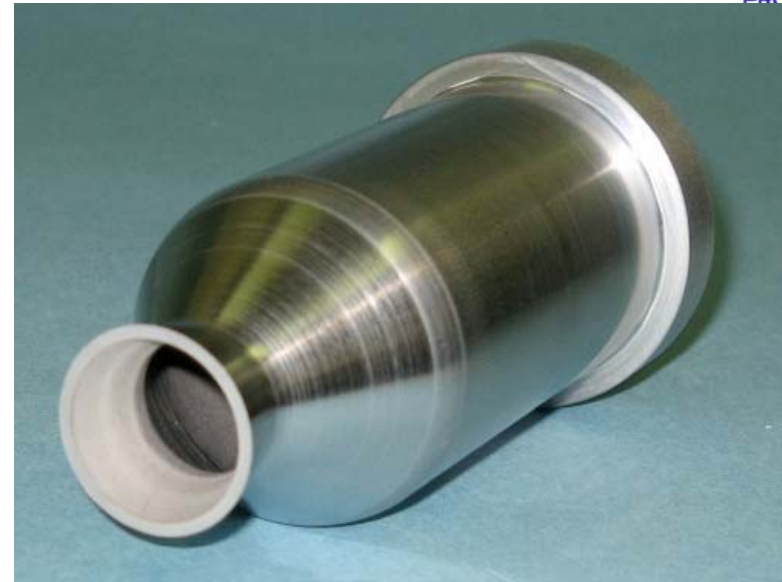


**Ir Layer Applied to Mandrel with El-Form**

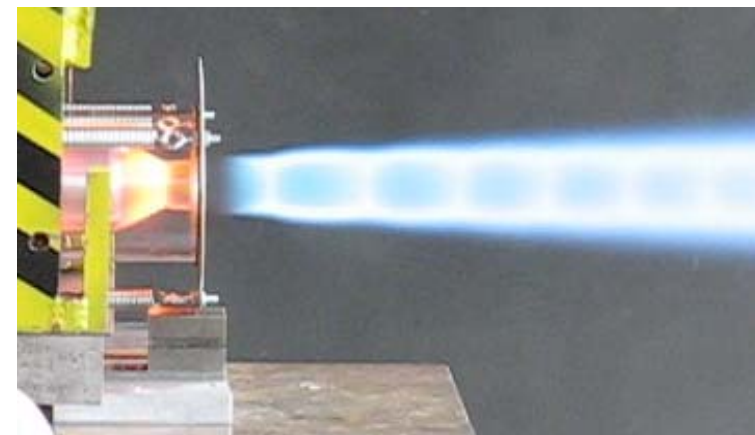


**Ir/Re Applied to Mandrel with El-Form  
(prior to machining)**

In-Space Propulsion Technology (ISPT)



**Completed EL-Form Ir/Re Nozzle**



**Hot-fire Test**





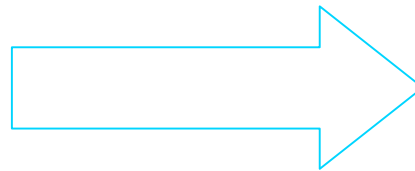


## Selection of Advanced Chamber Materials & Fabrication



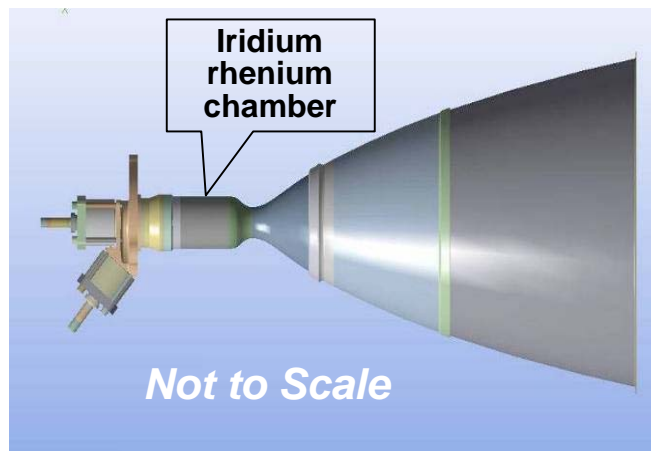
### CVD

- ❑ Present State of the art method for manufacturing iridium/rhenium chamber
- ❑ Manufacturing yield rate needs improvement



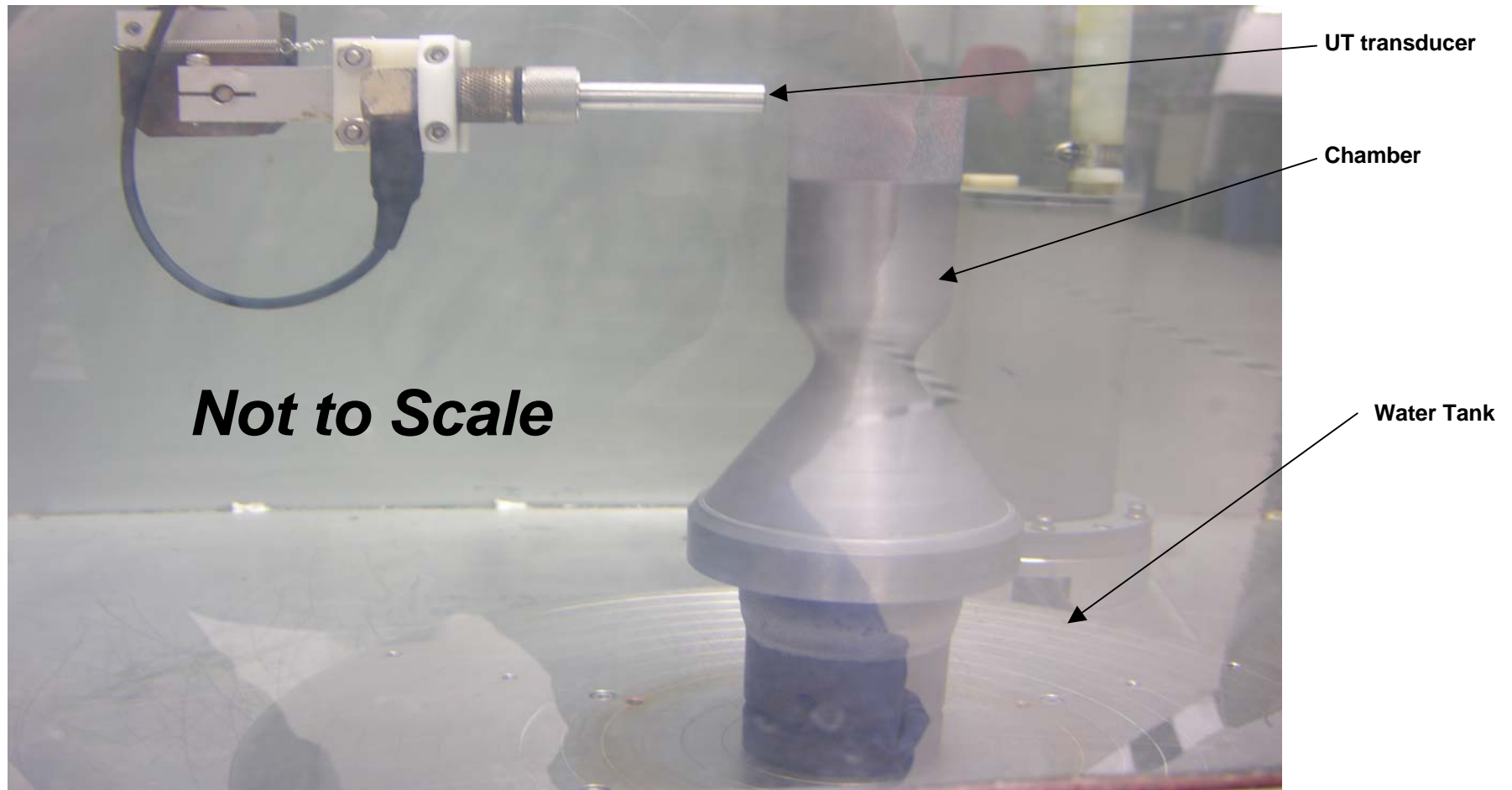
### EL-Form

- ❑ The method used to manufacture AMBR prototype
- ❑ 30% improvement on production cost (based on vendor quotations & invoice)





## AMBR Thruster Chamber Undergoing Ultrasonic Testing





## Risk Mitigation Test Objectives



- ☐ **Validate core engine design characteristics using a work horse chamber before committing to final engine build**
  - Verify performance of injector design (via  $c^*$  measurements)
  - Verify resonator design (via accelerometer measurements)
  - Finalize chamber length (via  $c^*$  measurements)



## Test Setup – Workhorse Chamber



- ☐ **Copper chamber with water cooling jacket**
  - Used to shorten turnaround time between runs, not for active cooling
- ☐ **Bolt-together construction enables swapping injector**
- ☐ **Flight-like valves and injector**
- ☐ **Truncated nozzle eliminates expense of heat resistant materials and fabrication plus thermal expansion mismatch with cooled chamber**
- ☐ **Nozzle performance extrapolated from known engine data**





# Test Setup – Engine Configuration



- ☐ **Full scale flow paths**
- ☐ **Variable length combustion chamber**
  - 2.6, 3.1, 3.6 and 4.1"
- ☐ **Propellants**
  - $\text{N}_2\text{O}_4$  Oxidizer and  $\text{N}_2\text{H}_4$  Fuel
- ☐ **Injector**
  - Flight-like titanium
  - Multiple unlike doublet
  - Fuel film cooling
  - Helmholtz resonators
- ☐ **Design nominal conditions**
  - Chamber Pressure: 275 psia
  - Thrust: 170 to 210 pounds
- ☐ **No flow calibration restrictors**
  - Pressure drop minimized
  - OF set by facility





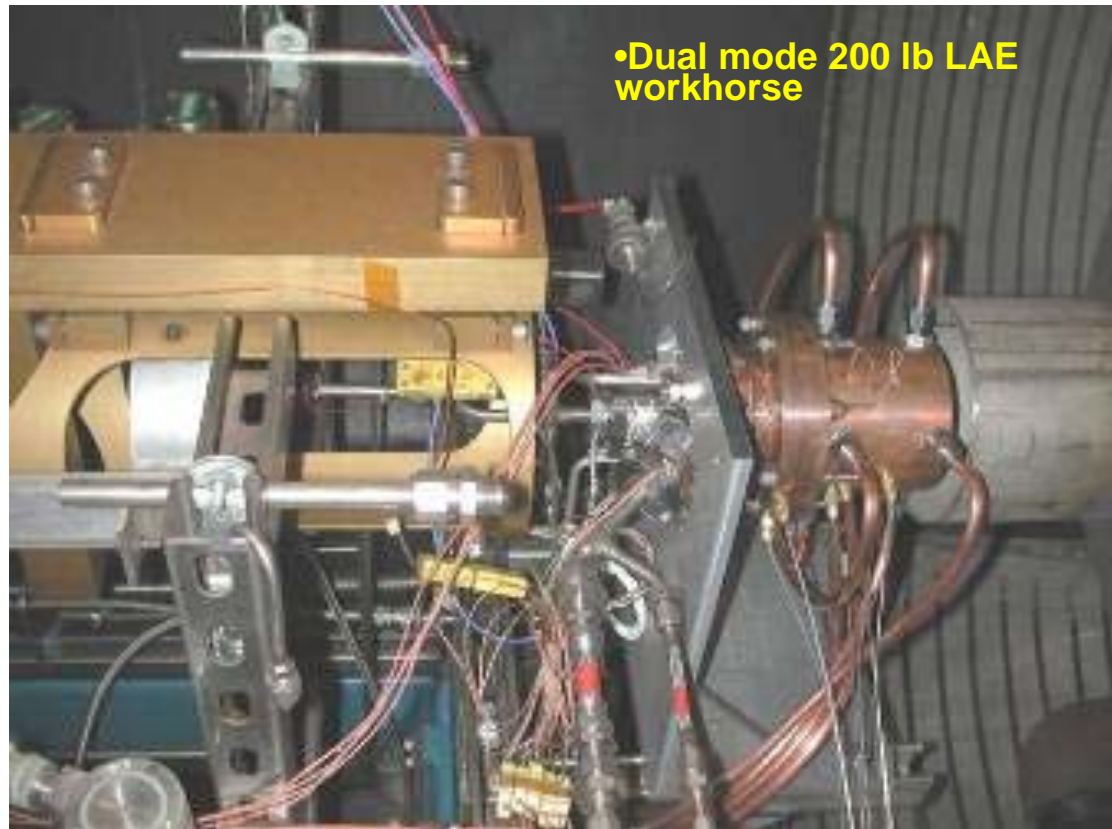
# Test Setup – Aerojet Redmond Altitude Test Cell



•Altitude cell and stage one diffuser and ejector



•Gas-fired boiler, cooling towers and 2 additional ejector stages



•Dual mode 200 lb LAE workhorse

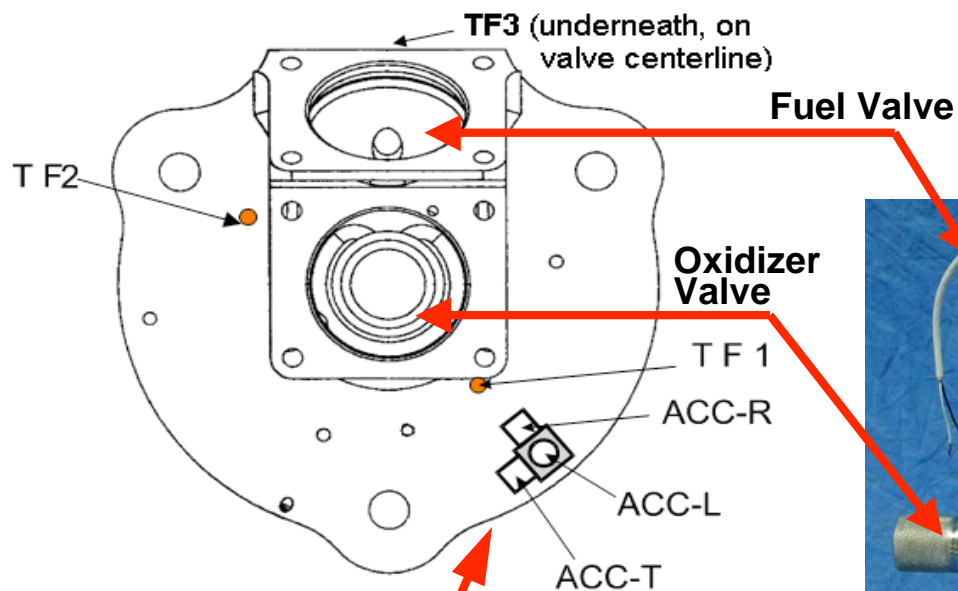
•Similar engine to AMBR in altitude cell, with cooling lines attached, poised to fire into diffuser

•Cell maintains less than 0.07 psia throughout firing for up to 330 pounds thrust bipropellant engines

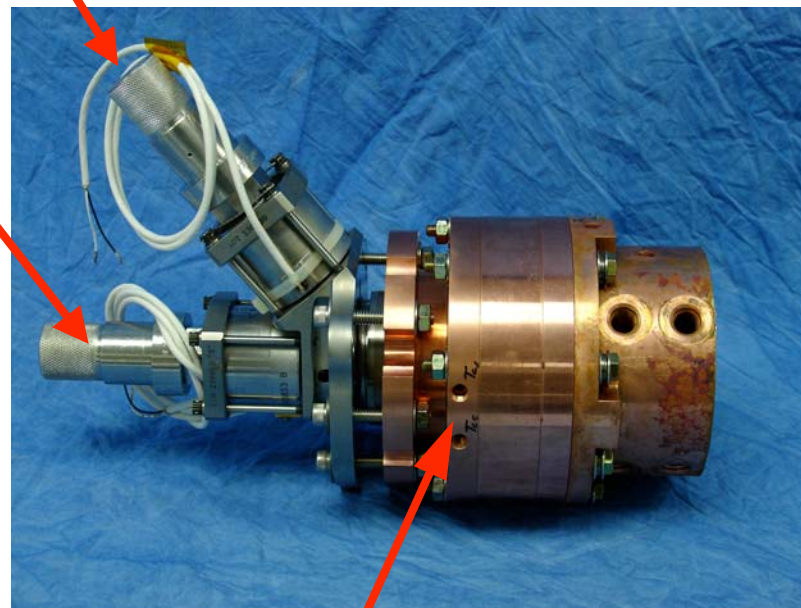




# Test Instrumentation



Thermocouples located to anchor thermal model



□ Three-axis accelerometer to measure ignition oscillation and damping for combustion stability monitoring

Additional instruments/measurements:

- propellant inlet pressures
- engine chamber pressure
- propellant flow meters



# Test Plan



Sequence Dash number	ON (sec)	OFF (sec)	Total Firings	PMO $\pm 5$ (psia)	PMF $\pm 5$ (psia)	O/F	Ox/Fuel Temperature $\pm 5$ (°F)	Comments
Trim	2	-	AR	428	430	1.200	70	
1	3	-	2	433	435	1.207	70	Nominal Pc, Nominal O/F
2	3	-	2	343	350	1.204	70	Low Pc, Nominal O/F
3	3	-	2	438	429	1.301	70	Nominal Pc, High O/F
4	3	-	2	328	365	1.046	70	Low Pc, Low O/F
5	3	-	2	430	465	1.125	70	High Pc, Low O/F
6	3	-	2	358	335	1.398	70	Low Pc, High O/F
7	3	-	2	440	422	1.308	70	Nominal Pc, High O/F
8	3	-	2	460	465	1.192	70	High Pc, Nominal O/F
9	3	-	2	422	439	1.164	70	Nominal Pc, Low O/F

Note: PMO = oxidizer feed pressure measured upstream of the propellant valve.

PMF = fuel feed pressure measured upstream of the propellant valve.

- ☐ Inlet pressures of 328-460 (oxidizer) and 335-465 (fuel) psia tested
- ☐ OF ratio of 1.046 to 1.398 tested (stoichiometric OF for  $N_2O_4$  /  $N_2H_4$  is 1.44)



# Test Objectives



## ☐ Characterize injector performance while varying:

- Feed pressures
- Mixture ratio
- Chamber length

## ☐ Demonstrate:

- Fast response
- Stable ignition
- Steady-State injector operation (dynamic)

## ☐ Performance goals:

- 335 seconds Isp

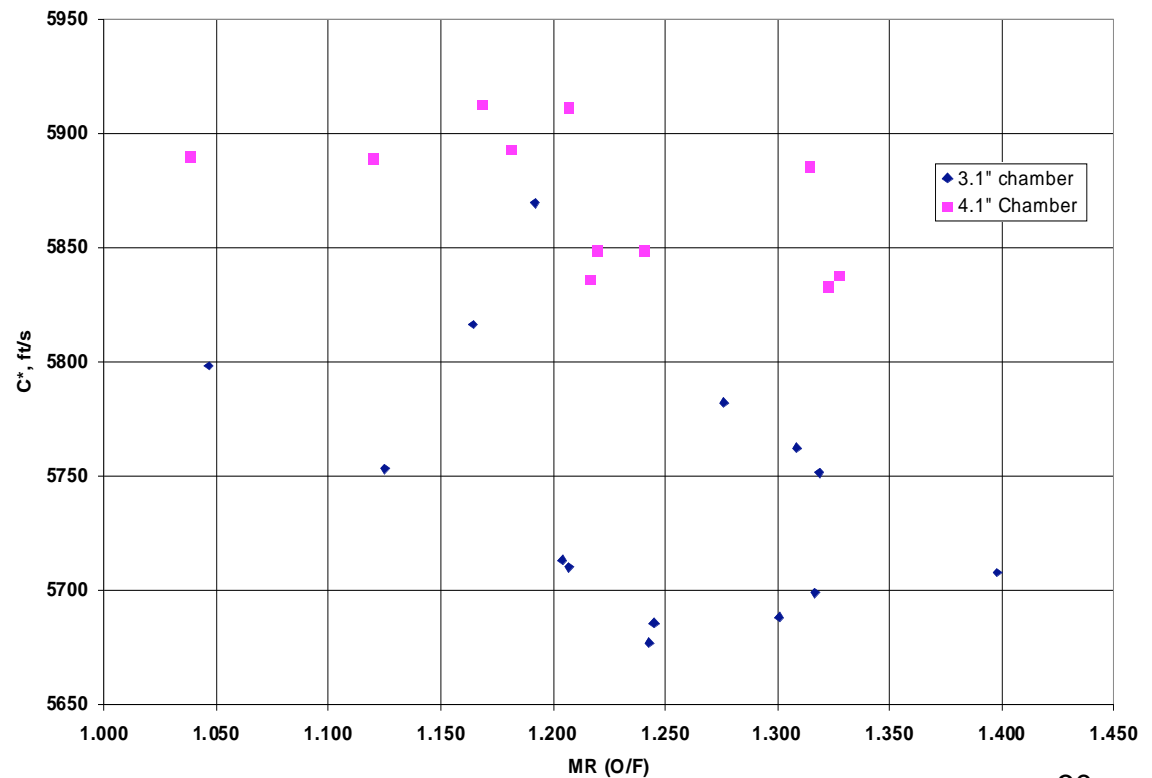
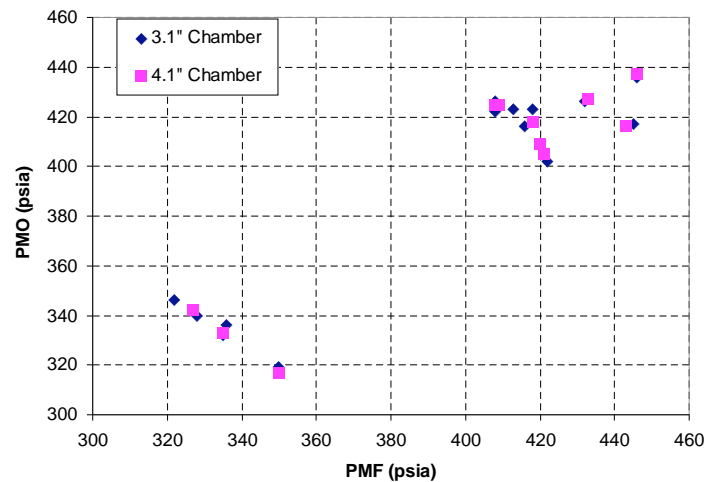


# Test Results



- ❑ 3.1 and 4.1 inch chambers tested
- ❑ Maximum performance seen at OF ~1.200 in 4.1" chamber
  - $C^* = 5849$  ft/s at design point
  - Design inlet pressure 430 psia
  - Max  $C^*$  5913 ft/sec = 1802 m/s
  - $I_{sp}$  (est.) > 335 sec

$$C^* = \frac{P_c \cdot A_t \cdot g_0}{(W_o + W_f)}$$

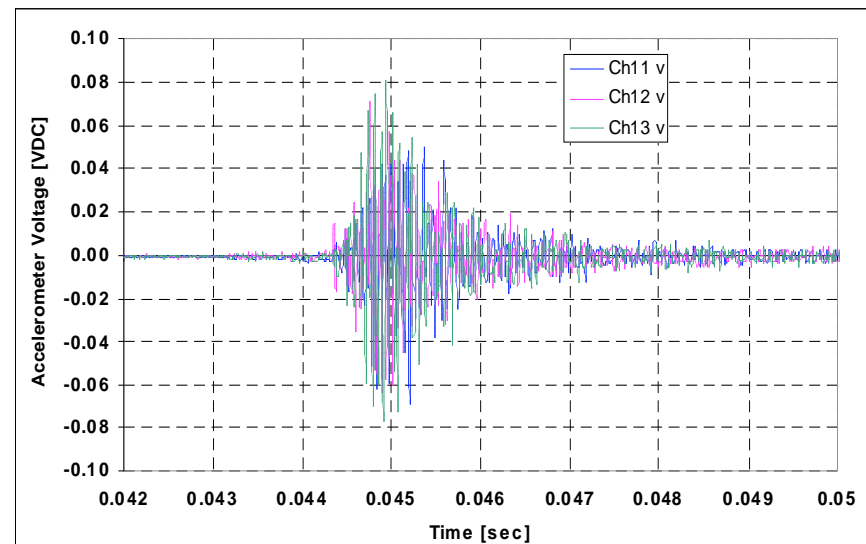
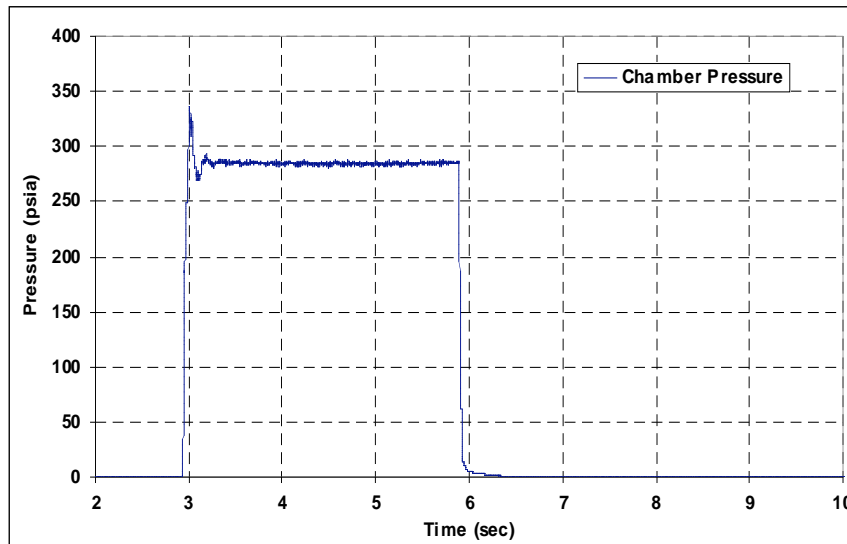




## Test Results (Continued)



- ☐ Dynamics and Combustion Stability
- ☐ Roughness approximately 3% peak-to-peak
- ☐ Start response time to 90% thrust ~60 msec
- ☐ Stop response time to 10% thrust ~30 msec
- ☐ Accelerometer trace shows damping from start transient within 5 msec





# Highlights of 2007 & Early 2008



- ❑ **Successful Baseline test** laid foundation for AMBR engine design
  - ❖ Thermal data,
  - ❖ Chug information,
  - ❖ and pressure, MR, and thrust information beyond baseline engine operating envelope collected for anchoring models
- ❑ **Engine performance target has been verified** in the risk mitigation test
- ❑ Prototype engine fabrication near completion
- ❑ Preparation in progress to **infuse AMBR thruster into planetary missions**





## Remaining Tasks



### ☐ **Complete AMBR fabrication (3<sup>rd</sup> Quarter 2008)**

- Injector assembly, combustion chamber, nozzle, and nozzle extension

### ☐ **AMBR performance envelope testing (4<sup>th</sup> Quarter 2008)**

### ☐ **Environmental Testing (2008/2009)**

- Vibration (Aerojet)
- Shock (JPL)
- Hotfire life test (Aerojet)